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Materials Testing for PV Module Encapsulation

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ABSTRACT

Important physical properties of materials used in PV module packaging are presented. High-moisture-barrier, high-resistivity, adhesion-promoting coatings on polyethylene terephthalate (PET) films have been fabricated and characterized for use in PV module application and compared to standard polymer backsheet materials. Ethylene vinyl acetate (EVA) and an encapsulant replacement for EVA are studied for their water vapor transmission rate (WVTR) and adhesion properties. WVTR, at test conditions up to 85°C/100% relative humidity (RH), and adhesion values are measured before and after filtered xenon arc lamp ultraviolet (UV) exposure and damp heat exposure at 85°C/85% RH. Water ingress is quantified by weight gain and embedded humidity sensors.

1. Background

The PV community has shown interest in replacing the glass backsheet in manufactured thin film PV modules with a lightweight, insulating, moisture-barrier backsheet and in finding an improved moisture barrier encapsulant that can replace EVA. In some module types, it is not necessary that the encapsulant transmit the solar spectrum. WVTR and adhesion properties of such an alternate could be superior at lower cost. The qualities for a glass-replacement backsheet are that it be insulating to prevent a conduction path from the back contacts to the grounded metal frame; prevent moisture ingress; adhere well to the lamination material before, during, and after damp heat and UV exposure; and provide a durable mechanical barrier to the environment.

As a substitute for using an expensive single polymer film such as poly (vinylidene chloride) (PVDC) or laminates such as Tedlar®-Aluminum-Tedlar® (TAT), oxide coatings on inexpensive polymers such as PET and biaxially oriented polypropylene (BOPP) [1-3] have been investigated. Although such insulating moisture barriers are routinely produced for the food-packaging industry [4], their requirements are much less stringent than what is believed to be necessary for PV modules to pass the "damp heat test". The "damp heat test" portion of the IEEE 1262 qualification specification calls for module exposure at 85°C and 85% RH for 1000 h.

The food packaging industry desires materials that have a WVTR < 1 g/m^2-day at ambient temperatures and humidity. PVDC is a commercially available polymer that meets these criteria; but at 85°C, this polymer is an extremely poor barrier and exhibits a WVTR greater than 300 g/m^2-day [5].

During service exposure, adhesive bonds between encapsulant and superstrate/substrate materials of PV modules can weaken, leading to moisture ingress and/or delamination failure. Thus, any backsheet material must also exhibit excellent adhesion to the encapsulant material, which is typically a formulated EVA. Thin film coated polymer backsheets should be good barriers against moisture ingress, electrically insulating, UV stable, and highly adherent to the encapsulant. The thin film coating should also be very adherent to the substrate.

2. Experimental

The WVTR of inorganic barrier coats on PET, several commercially available candidate backsheet constructions, EVA, and an EVA replacement candidate ("LAF" from TruSeal) have been measured over a range of temperatures using a Mocon Permatran-W® 3/31 instrument as per ASTM F1249-01 [6]. The Mocon Permatran-W® 3/31 has been adapted to interface with external (remote) cells that enable measurements at 85°C. To complement WVTR studies of moisture ingress through polymeric encapsulant laminates, gravimetric and embedded moisture sensor studies show that small but significant levels of moisture adsorb and permeate encapsulants.

These candidate backsheets have also been vacuum-laminated to EVA (STR Photocap 15295P) or to LAF and then to a front glass superstrate (usually AFG Krystal Klear, 3 mm thick) to replicate backsheets in module constructions. Figure 1 is a not-to-scale schematic of a test article construction used for accelerated exposure testing (AET). The test modules were subsequently exposed to one of these accelerated testing environments: i) filtered xenon arc lamp radiation in an Atlas Ci4000 Weather-Ometer® (light intensity ~1 sun, 65ºC/10%RH); or ii) damp heat (dark, 85ºC/85%RH).

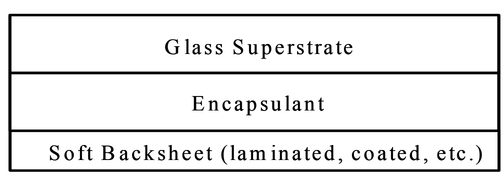

Figure 1. A schematic of the test article construction used for accelerated exposure tests.

To investigate any changes at the laminate interfaces as a function of AET, peel tests were conducted on samples using an Instron 5500R, as prescribed by ASTM D903-98 [7].

3. Results and Discussion

For a backsheet to be used as a replacement for glass, it must meet the previously stated requirements of being insulating and preventing moisture from reaching the back contact, plus not delaminate or crack after lamination, and be weatherable. All samples discussed herein have been stressed and characterized with respect to these criteria.

3.1 Water Vapor Transmission Rates (WVTR)

Table 1 presents the measured WVTR at 37.8°C and 85% RH of candidate soft backsheets and encapsulants that include uncoated PET, PET coated at NREL and by an industrial collaborator (AKT), commercially available backsheet materials, EVA, and LAF. The coated-PET constructions exhibit a dramatic improvement over the uncoated polymer. Coated PET has two significant advantages: it does not contain a conductive layer such as aluminum in the commercial TAT construction, nor does it contain a fluoropolymer (Tedlar®) that would require surface modification to improve adhesion to encapsulants.

Table 1. WVTR for polymer laminates at 37.8 °C and 85 % Relative Humidity.

Material	Thickness (mm)	WVTR (g/m^2-d)
PET	0.18	2.3
NREL Coated PET	0.18	0.3
AKT Coated PET	0.18	0.05
Tedlar®/PET/EVA (TPE)	0.20	3.0
Tedlar®/Al/Tedlar® (TAT)	0.10	0.04
EVA	0.4-0.5	27-33
TruSeal LAF	0.84	0.38

We have successfully interfaced our Mocon Permatran-W® 3/31 instrument with remote cells and have acquired WVTR data at 60º and 85°C with 100% RH. The cells, machined from stainless steel to prevent corrosion problems at elevated temperatures, have been installed, and calibrated. Metal moisture barriers were used to check for leaks and characterize cell noise. Melinex 6429 PET was tested in each cell over a range of temperatures to check for variations between the two remote cells and between the remote and local cell data. Arrhenius plots were made for materials tested at elevated temperatures (Fig. 2); the resulting linear trendlines display the Fickian nature of the materials and demonstrate good agreement between local and remote cell data.

3.2 Effect of Accelerated UV Exposure on Adhesion

Table 2 details the measured interfacial adhesion between candidate backsheets and an EVA encapsulant as a function of UV exposure in an Atlas Ci4000 Weather-Ometer® at ~1-sun light intensity, 65°C, and 10% RH. Peel strength values greater than 10 N/mm were indicative of cohesive failure of EVA and represent lower limits for the EVA/glass interfacial adhesion. Values between 1 and 10 N/mm were measured EVA/glass peel strengths; values <1 N/mm represent backsheet/EVA peel strengths. In the case of TAT, the EVA/glass adhesion could not be measured because failure occurred at the Tedlar®/aluminum interface even before weathering. As can be seen in Table 2, coated PET has dramatically improved initial peel strength compared to uncoated-PET. However, after 1200 h exposure in the Ci4000, the peel strength of coated-PET samples decreases by a factor of 2-3. We are continuing to pursue ways to improve weathered adhesion properties with our industrial collaborators and in-house.

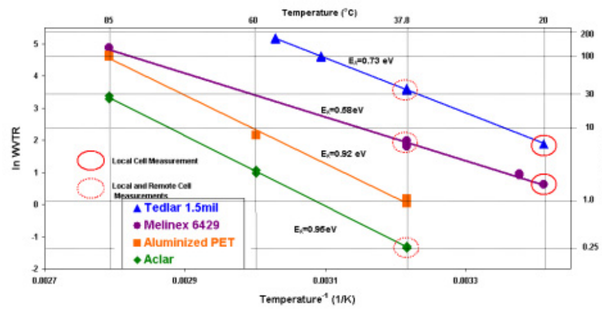

Figure 2. Arrhenius plot of WVTR for various backsheet materials as measured with remote cells.

Table 2. Peel strength (N/mm) at the EVA/coating interface as a function of exposure time in an Atlas Ci4000 Xenon Weather-Ometer (light intensity ~1 sun, 65°C, and 10% RH).

Backsheet	Time of Ci4000 Exposure (h)			
	0	400	800	1200
AKT Coated PET	11.4	13.0	7.2	6.4
NREL Coated PET	11.4	12.1	6.9	4.2
Uncoated PET	0.5	0.5	0.5	
TPE	7.5	7.0	0.5	
TAT	0.5	0.6	1.5	

3.3 Coating Stress and Cracking

Although these coated PET samples exhibit good adhesion, weatherability, and low water vapor transmission rates, they can also crack during and/or after lamination. An example of such cracking can be seen in Fig. 3a. Figure 3b is a photomicrograph of a non-cracked sample having the same construction and lamination procedure as the sample shown in Fig. 3a. The cracking was attributed to stress in the films, and deposition parameters were adjusted to decrease the residual stress. As can be seen in Fig. 4, cracking was not observed at compressive stresses less than ~ 5 x 10^9 dynes/cm^2.

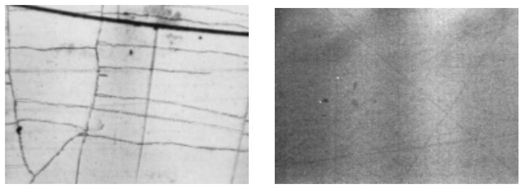

Figure 3. Optical microscope photograph (40x magnification) of samples that cracked (a, left) and did not crack (b, right) during lamination to EVA and a glass superstrate.

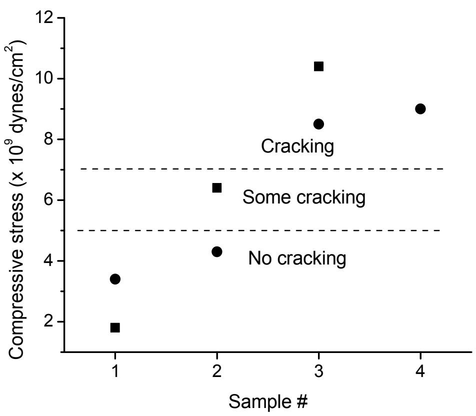

Figure 4. Correlation between compressive stresses and cracking for several inorganic thin film coatings on PET.

3.4 Effect of Damp Heat Exposure on Adhesion

Samples that did not exhibit cracking after/during lamination were exposed to either UV (as discussed above) or damp heat stress conditions. Damp heat weathering was provided by a controlled temperature/humidity chamber (no light, 85°C, 85% RH). The adhesion values of samples as a function of exposure time in the damp heat chamber are shown in Table 3. The various ranges of peel strength values have the same physical meaning as explained for the UV-exposed samples. Data in Table 3 indicate that short-term exposure to damp heat is not too deleterious; however, longer-term exposure (~100 h) can be very severe. PET film coated in-house by sputter deposition exhibited very low peel strength values after ~100 h exposure to damp heat. Samples failed at the coated-PET / EVA interface; all samples peeled readily by hand, and values were too low to measure. This was true for samples prepared having both sides of the film coated (the outer coating was intended to keep moisture from degrading the adhesive properties of the inner coating/EVA interface). Single and double-sided coated samples prepared by a different deposition process (glow discharge) by AKT also resulted in failed adhesion (at the same interface) after extended damp heat exposure.

Table 3. Peel strength (N/mm) values for Backsheet/EVA/Glass constructions as a function of damp heat (85ºC/85%RH) exposure.

Backsheet	Time of Damp Heat Exposure (h)		
	0	16	115
AKT Coated PET	11.3	10.6	*
NREL Coated PET	10.9	10.6	*
Uncoated PET	0.4	0.5	0.1
TPE	9.5	8.3	8.5
TAT	0.8	--	--

* Peeled by hand; values too low to measure

3.5 Moisture Ingress and Adhesive Bonds

STR's 15295P EVA contains an adhesion-promoting silane coupling agent that undergoes condensation reactions at the silica glass surface during lamination. For this reaction, there is also a reverse hydrolysis reaction. A simple example of this surface equilibrium reaction is:

$$RR'R''Si(OH) + HO\text{-}Si_{(s)} \Leftrightarrow H_2O + RR'R''Si\text{-}O\text{-}Si_{(s)} \quad (1)$$

where $Si_{(s)}$ denotes a silicon atom of the glass surface that is connected to the bulk [8].

If there is sufficient concentration of water in the near-surface/interface vicinity, the equilibrium is shifted toward the reverse reaction and the interface will increasingly favor surface hydrolysis. Once hydrolyzed, the number of bridging $\text{-}Si\text{-}O\text{-}Si_{(s)}$ surface groups is reduced and the glass/EVA interfacial adhesion is reduced correspondingly. Equilibrium depends on the solubility of water vapor in EVA and the number of surface bonds formed between the silicon-containing molecule and the glass surface.

The experimental LAF from TruSeal, still in test, has lower initial adhesion (~1 N/mm, Table 4) than EVA/glass, but has a very hydrophobic surface. It is unknown whether coupling agents are used, but adhesion measurements as a function of damp heat exposure will indicate whether adhesion to glass will remain adequate to protect PV cells from moisture.

Table 4. Peel strength (N/mm) values for Backsheet/LAF/Glass constructions as a function of damp heat (85ºC/85%RH) exposure.

Backsheet	Time of Damp Heat Exposure (h)			
	0	15	105	498
Melinex PET	0.6	1.4	1.1	1.3
Mylar PET	0.7	1.4	0.9	0.7
TPE	0.7	1.1	0.9	*

*LAF failed cohesively

Gravimetric studies of moisture ingress in polymeric encapsulant laminates show small but significant levels of moisture that adsorb and permeate these encapsulants and impact long-term PV module performance (Fig. 5). Both saturation and transport rates are measured in conjunction with temperature and humidity exposure to allow an understanding of how water-saturation levels affect module-package integrity. Correlation between peel strength and moisture uptake at specific module material interfaces will be studied in future work. Early work suggests we need to refine our technique to better measure moisture-saturation values on the order of three to four tenths of a percent.

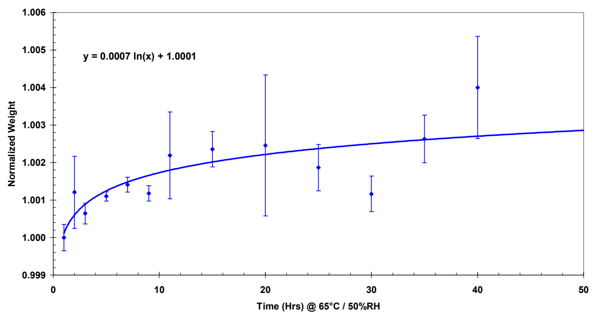

Figure 5. Mean normalized moisture uptake for TPE/EVA/TPE.

The amount of water vapor that diffuses into the encapsulant is crucial for determining the overall stability of the glass/encapsulant interface. However, this also suggests that the EVA/coating interface either disfavors condensation reactions and is more difficult to hydrolyze or that there is a different type of adhesive bonding/reaction taking place. To measure water actually diffusing to the interface, and subsequently, the drying-out phase, humidity sensors have been embedded in test structures.

Summary

Physical properties important for materials used in PV module packaging are presented. High-moisture-barrier, high-resistivity coatings on polyethylene terephthalate (PET) films have been fabricated at NREL and at AKT and characterized for use in PV module applications and compared to standard polymer backsheets materials. Initial efforts produced films that cracked during lamination. Subsequent films, exhibiting similar improved water vapor barrier properties, but lower compressive stress, have been produced that do not crack during lamination.

EVA and a replacement for EVA are studied for their water vapor transmission rate (WVTR) and adhesion properties. LAF is very hydrophobic and has a WVTR considerably lower than EVA. While its initial adhesion is only 10% of EVA's, peel strength values remain fairly constant during damp heat exposure at 85°C/85%RH. Water ingress is measured by weight gain and embedded humidity sensors.

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The authors appreciate materials provided for use in the various sample configurations that have been tested; these include EVA from STR, LAF from TruSeal, glass from AFG, TPE and TAT from Madico, and PET from DuPont. Barrier coatings were deposited by Greg Barber at NREL and by AKT; AKT also measured residual stress of deposited films. This work was conduced at NREL under U.S. Department of Energy Contract No. DE-AC36-99-GO1337.

REFERENCES

[1] B.M. Henry et al. “A microstructural study of transparent metal oxide gas barrier films,” *Thin Solid Films* **355-356** (1999), pp. 500-505.

[2] Y.G. Tropsha and N.G. Harvey. “Activated rate theory treatment of oxygen and water transport through silicon oxide/poly(ethylene terephthalate) composite barrier structures,” *J. Phys. Chem. B* **101** (1997), pp. 2259-2266.

[3] A.K. Plessing, et al., “Progress and performance of new encapsulating materials,” *European PV Meeting*, Glasgow, Scotland, 2000.

[4] J. Felts, “Transparent barrier coatings update: flexible substrates,” *Society of Vacuum Coaters, 36th Annual Technical Conference*, April 25-30, 1993, Dallas, TX, pp. 324-331.

[5] Mocon Inc., private communication.

[6] F1249-01 Standard Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor (American Society for Testing and Materials, West Conshohocken, PA, USA, 2001).

[7] D903-98 Standard Test Method for Peel or Stripping Strength of Adhesive Bonds (American Society for Testing and Materials, West Conshohocken, PA , USA, 2001).

[8] E.P. Pleuddemann. *Silane Coupling Agents*, (Plenum Press, NewYork) 1991, pp. 115-152.

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